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Cover crop effects on the fate of N following soil application of swine manure

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Abstract Cereal grain cover crops increase surface cover, anchor corn *(Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] residues, increase infiltration, reduce both rill and interrill erosion, scavenge excess nutrients from the soil, and are easily obtained and inexpensive compared to other cover crop options. The use of cereal grain cover crops in fields where manure application occurs should increase nitrogen (N) recovery and cycling for use in subsequent crops. The objectives of this study were to determine if a rye *(Secale cereale* L.) cover crop increases N retention after soil application of swine lagoon slurry. Experiments were conducted in a controlled environment chamber using plastic buckets as the experimental units. Three manure-N loading rates (no manure, low, high) were applied to soils with and without a rye cover crop. A partial N balance was determined from measurements of NO_3 leaching, N_2O and NH_3 emissions, cover crop N uptake, and NO_3 + NH_4 remaining in the soil. Cumulative nitrate load in the drainage water was less than 0.31 g m^{-2} NO_3-N for rye treatments regardless of the manure rate, however in the fallow treatments, at the high manure rate NO_3 leaching losses were 6.28 and 3.77 g m^{-2} NO_3-N, for experiments 1 and 2, respectively. Rye N uptake ranged from 2.95 g N m^{-2} to 10.7 g N m^{-2}, and was related to manure rate. Rye had lower cumulative N_2O emission than the no rye treatment for the high manure treatment. Ammonia emissions were low for all treatments during both experiments, which was probably related to the rapid manure incorporation after application. Rye can increase N retention, reduce cumulative N_2O emissions, and reduce cumulative N load in drainage water when manure is applied to soils. Nitrogen balance calculations in the cover crop treatments accounted for less than the equivalent of 50% of the added manure N. We speculate that the living rye plants may have increased immobilization of N in the organic N pools.

Keywords Nitrate leaching · Ammonia volatilization · Nitrous oxide emissions

Introduction

Managing manure in agricultural cropping systems to retain nutrients and prevent adverse off-site impacts presents difficult challenges, especially related to managing N losses. Sharpley et al. (1998) reviewed many of these challenges of managing manure N losses, which include: (i)

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uncertainties in manure N composition; (ii) volatile N losses (i.e., denitrification and NH_3 volatilization) during storage and handling, and application; (iii) difficulty in proper application, and (iv) differences in N mineralization rates after land application. These investigators suggested that management of the soil NO_3 pool was a key factor in development of strategies to reduce NO_3 leaching to groundwater.

Use of cover crops is known to be an effective strategy in reducing the soil nitrate pool. Meisinger et al. (1991), in a review of past studies on cover crops summarized that the nitrate concentration in leachate can be reduced from 20% to 80% by using cover crops, and that grass cover crops are more effective than legumes. In addition to reviewing the literature, these investigators used the simulation model EPIC to estimate the effect of cover crops in a continuous corn system on leachate water quality for 10 US locations. For Ames, IA, their simulation concluded that a small grain winter cover crop would reduce the nitrate load to water leaching through the soil (or tile effluent) by 64% and nitrate concentrations by 50% (Meisinger et al. 1991). Dinnes et al. (2002) reviewed nitrogen management strategies to reduce nitrate leaching in tile-drained Midwestern soils. In their conclusions, among other suggestions, they recommended incorporating cover crops in the corn–soybean rotation to reduce the potential for nitrate leaching. This conclusion is supported by studies of Logsdon et al. (2002) who, in a controlled-environment lysimeter study that simulated an Iowa climate, showed that oat (*Avena sativa*) and rye cover crops in a corn–soybean rotation reduced nitrate losses by over 70% in three simulated years.

Cover crops may reduce nitrogen losses from agricultural systems by reducing both nitrate leaching and ammonia and nitrous oxide transport to the atmosphere. Previous studies have not simultaneously evaluated the effect of a rye cover crop on leaching and gaseous losses of N following an application of liquid swine manure. The objective of our study was to investigate the effect of a rye cover crop on retention and losses of swine manure N applied to soil, and to examine the effects of a rye cover crop on N cycling by performing a partial N balance with and without swine manure additions.

Materials and methods

Experimental setup

Experiments investigating cover crop effects on N cycling following swine manure additions were performed in a controlled environment chamber programmed for a 14 h light period, 18°C day temperature, and 15 °C night temperature. This temperature regime corresponds to the 54 y mean monthly September temperature for mid Iowa of 17.7°C. The experimental design was a randomized complete block design with 2 × 3 factorial arrangement of cover crop and swine manure treatments. The cover treatments were: (i) a rye cover crop and (ii) no rye cover crop. The swine manure treatments were: (i) a control (no manure), (ii) a phosphorus-based manure application rate (low manure), and (iii) a nitrogen-based manure application rate (high manure). The treatments were replicated four times and the experiment was conducted twice (experiment 1 and 2). Experiment 1 was conducted over a period of 40 days and experiment 2 over a period of 35 days.

The experimental units were plastic buckets (high density polyethylene, 0.27-m diameter and 0.35-m height) containing soil and attached to a drainage collection system. Each plastic bucket was lined with a Teflon plastic bag to minimize ammonia absorption by the plastic bucket. To provide drainage for each bucket a 48-mm diameter and 60-mm long ceramic cup with an air entry value of 50 kPa was placed on the bottom. One end of the ceramic cup was sealed with a rubber stopper which had plastic tubing inserted through its center. This tubing was later connected to a vacuum pump that maintained a vacuum of 9.8 kPa and pulled any water that collected in the ceramic cup into a collection flask. The bottom of each bucket and the ceramic cup were covered with 5.3 kg of coarse construction sand. On top of the sand, 12.0 kg of air-dried clay loam soil was applied in layers and settled by tapping the bucket against the floor. Soil for both experiments was collected from the Iowa State Agronomy and Agricultural Engineering Research Center located 12 km west of Ames, IA. The soil was a Nicollet clay loam (fine-loamy, mixed, superactive, mesic Aquic Hapludolls; Andrews and Diderikson, 1981), which was air-dried, passed through a 10-mm mesh sieve, and mixed. The soil used in these experiments had a pH of 6.1, was 44% sand, 28% silt, 28% clay and had organic C and N contents of 1.83% and 0.14%, respectively.

To prepare the soil in each bucket for the experiments and to more closely simulate a field soil, 14 soybean seeds were planted in each bucket and the soybean were allowed to grow for 30 days. The soybean plants were then cut off at the soil surface and rye (‘Rymin’) was planted (approx. 100 seeds/bucket) in 12 of the 24 buckets being prepared for each experiment. The rye was allowed to grow for 28 days before the application of the manure treatments. A total of 48 buckets were prepared, 24 for each of the two experiments.

Manure application

Liquid swine manure was applied by cutting a trench across the center of the bucket about 5 cm wide and 5 cm deep, pouring the manure into the trench, and then covering the liquid manure with the soil that had been removed from the trench. Two manure rates were used. In experiment 1 the low rate (phosphorus-based manure rate) added, on average, 2.8 g P m^{-2} and 7.5 g N m^{-2} and the high rate (nitrogen-based rate) added 6.4 g P m^{-2} and 19.5 g N m^{-2}. In the second run of this experiment (experiment 2) the low manure rate added, on average, 1.1 g P m^{-2} and 3.0 g N m^{-2} and the high manure added 6.8 g P m^{-2} and 17.9 g N m^{-2} Manure properties are presented in Table 1.

Table 1 Composition of manure used in the two experiments

	Experiment 1	Experiment 2
Dry matter (g kg^{-1})	40	25
Total N (g N kg^{-1})	3.1	2.5
Ammonium N (g N kg^{-1})	1.6	1.6
Nitrate N (mg N kg^{-1})	12.7	3.5
Phosphorus (g P kg^{-1})	1.3	0.9
Potassium (g K kg^{-1})	1.2	1.1
pH	7.3	7.3

Water application, nitrate leaching, and calculation of cumulative drainage and evapotranspiration

After the buckets were filled with sand and soil, but before growing soybean or rye in the buckets, each bucket and its contents were weighed, 4,000 ml of a 0.005 M calcium chloride solution were applied over 4 h, and the soil surface was covered with plastic. Calcium chloride was included in all subsequent water applications to the buckets to prevent soil aggregate dispersion. A 9.8 kPa suction was applied to the ceramic cup in each bucket and the drainage water collected. After 48 h, the buckets were weighed again to determine weight of the bucket and soil system at a relative ‘‘field capacity’’ of the soil–sand column. This ‘‘field capacity’’ bucket weight was then used to estimate the amount of water that needed to be added to the buckets to produce drainage in all 24 buckets. Before the manure treatments were applied (3 days, experiment 1; 4 days, experiment 2), all buckets were weighed and the amount of water required to rewet the driest bucket to produce an estimated 350 ml of drainage was added to all the buckets. In both experiments, the driest bucket each week always had a rye cover crop growing in it. For all subsequent weekly waterings, all buckets received an amount of water that was based on the average difference between the current weight and the ‘‘field capacity’’ weight of the buckets with a rye cover crop plus an additional 350 ml. If no drainage was collected from some buckets within 12 h, then an additional 300 ml was added the next day to all buckets so that all buckets in each experiment had some drainage each week. This watering regime resulted in, on average, approximately 2,200 ml of water added to each bucket every week, which was equivalent to approximately 36 mm of water/week. This water application rate was higher than the 54 y average weekly rainfall during the month of September in mid Iowa (18 mm/week), but within the range of values observed over the past 54 years (range: 1.0–51 mm).

Each week, drainage water was collected from each bucket in individual flasks to which 0.5 ml of 10 N sulfuric acid had been added, weighed, and then subsampled for nitrate and ammonium analyses. Drainage water subsamples were analyzed for NO_3-N (NO_3-N + NO_2-N) and NH_4-N using the colorimetric reaction as described by Keeney and Nelson (1982) on a flow-injection autoanalyzer. Only trace amounts of NH_4 were occasionally observed in the drainage water. Weekly nitrate loss was calculated by multiplying nitrate concentration by weight of drainage water collected during a week. Cumulative nitrate loss was calculated by summing the week nitrate loss in all drainage water collected after manure application (Day 0).

Cumulative drainage was calculated by summing the weekly drainage after Day 0. Weekly evapotranspiration (ET, g), which is only evaporation for the buckets without rye, was calculated using the following equation:

$$\mathrm{ET} = \mathrm{BW}_t - \mathrm{BW}_{t+1} + \mathrm{WA} - \mathrm{L}$$

where BW_t = bucket weight at the start of the week before water application (g), BW_{t+1} = bucket weight at the start of the next week (g), WA = water applied during the week (g), and L = drainage water collected (g). Cumulative ET was calculated by summing weekly ET, beginning with the day of the first water application following Day 0.

Weekly gravimetric water content was calculated by subtracting bucket tare weights and the dry weights of the soil + sand from BW, and then dividing by the total dry weight of soil + sand. Average gravimetric water content was calculated by averaging the weekly values.

Ammonia emissions

Ammonia fluxes were measured by an open chamber method. Ammonia flux chambers were 0.3 m in diameter by 0.1 m tall and were fabricated from 0.3 m diameter PVC pipe. The inside surfaces of the chambers were coated with Teflon tape to reduce ammonia deposition on chamber walls. Each chamber had inlet port and outlet ports made from low density polyethylene fittings. Ammonia flux measurements were initiated by placing the chambers on the buckets. An acid trap was attached to the outlet port of each chamber. Acid traps (Midget Bubbler with Frit, Supelco, Bellefonte, PA)[1] consisted of glass tubes with threaded tops containing an inlet port connected to a glass frit submerged in 20 ml of 0.1 N H_2SO_4, and an outlet port connected to a vacuum pump. The inlet tube of each trap was connected to one port of a chamber, and when the vacuum pump was turned on, chamber headspace air was drawn through the bubbling frit (approximately 150 ml min$^{-1)}$ submersed in the acid contained in the glass tube. In experiment 1, chambers were deployed for a 1 h period every day for the first 7 days following manure application, then every 2 days over the next 14 days, and then at weekly intervals for the next 2 weeks. In experiment 2, chambers were deployed for 3 h periods each day for the first 3 days following manure application, then at weekly intervals thereafter. At the start of each experiment ammonia flux measurements were initiated within 1 h after manure additions. Ambient air was also drawn through an acid trap each time NH_3 flux measurements were performed to serve as measurement blanks. Occasionally, when moisture condensation was observed after the chambers were removed, a dry filter paper (Whatman #42) was used as a swab to collect the condensate. The filter paper was then extracted with acid to determine ammonium concentration. Acid traps were analyzed for ammonium using the colorimetric method of Kempers and Zweers (1986). The flow rates used in our study resulted in less than 2 headspace changes/hour, which is substantially lower than the value of 15 air exchange volumes/min recommended by Kissel et al. (1977) for field-deployed chambers. Our low air exchange rates may have resulted in smaller NH_3 emissions than would have been observed under higher wind velocities present in the field, however, our NH_3 chamber exchange rates were reflective of the growth chamber conditions used in these experiments. Despite the fact that these conditions did not duplicate field conditions, the ammonia emissions

[1] Mention of trade names or proprietary products does not indicate endorsement by USDA and does not imply its approval to the exclusion of other products that may be suitable.

we measured would be valid as comparisons across treatments.

Nitrous oxide emissions

Following the measurements of NH_3 emissions, N_2O flux measurements were performed using a different chamber design and sampling protocol. Nitrous oxide flux measurements were performed daily by placing vented chambers (0.3 m diameter × 0.1 m tall) on the buckets and collecting gas samples 0, 30 and 60 min following chamber deployment. Chambers were constructed from PVC and covered with reflective tape. At each time-point, chamber headspace gas samples (10 ml) were collected with polypropylene syringes and immediately injected into evacuated glass vials (6 ml) fit with butyl rubber stoppers. Nitrous oxide concentrations in samples were determined with a Shimadzu gas chromatograph (Model GC17A, Shimadzu, Columbia, MD) equipped with a ^{63}Ni electron capture detector and a stainless steel column (1/8″ diameter × 6′ long) with Porapak Q (80–100 mesh). Samples were introduced into the gas chromatograph using an autosampler. Nitrous oxide fluxes were computed from the change in N_2O concentration with time, and cumulative N_2O emissions were calculated by linear interpolation and numerical integration between measurement times.

Plant sampling and soil analyses

At the end of each experiment rye plants were cut at the soil surface, dried (60°C), weighed, and ground in preparation for total C and N analysis. Following removal of the shoots, the entire soil mass (+ roots) was excavated from the buckets and kept separate from the sand at the bottom of the bucket. The excavated soil from each bucket was passed through a 20 mm sieve, mixed, and sub samples collected. A similar process was followed for the sand in each bucket. During this process, as many roots as possible were collected by hand, especially those roots still connected to the crowns of the rye plants and those roots remaining on the sieve. The remaining roots were removed from the soil using water and 2-mm mesh screens in a hydropneumatic elutriation system (Smucker et al. 1982). All collected roots and debris were rinsed again with water, stored at 5°C in a 50% isopropyl alcohol and water solution, and later cleaned by manually removing debris. After debris removal, the roots were dried, weighed, and ground for total C and N analysis. Rye shoot and root tissue were analyzed for C and N content using the dry combustion method (Schepers et al. 1989) on a Carlo-Erba NA1500 NCS elemental analyzer (Haake Buchler Instruments, Paterson, NJ). The sand and soil subsamples were extracted with 2 M KC1 and inorganic N ($NO_3^- + NO_2^- + NH_4^+$) was determined on the KC1 extracts by colorimetric methods using a Lachat autoanalyzer (Lachat Instruments, Mequon, WI) following the procedure described by Keeney and Nelson (1982).

Statistical analyses

Treatment effects were assessed using ANOVA and differences assessed by the Fisher protected LSD method. Statistical tests were performed with SigmaStat software (SigmaStat v. 2.03, SPSS, Inc., Chicago, IL) and SAS version 8 (SAS Institute Inc., Cary, NC).

Results

Cumulative gaseous losses of N_2O and NH_3, and leaching losses of NO_3, along with measurements of mineral N ($NO_2 + NO_3 + NH_4$) remaining in the soil and N uptake by the rye are presented in Table 2. Total N volatilized as NH_3 was low in both experiments and ranged from 0.001 g N m^{-2} to 0.066 g N m^{-2} across all the treatments. Although NH_3 fluxes were low, significant differences were noted. In experiment 1, addition of high rates of manure resulted in significantly higher NH_3 emissions than either the low or zero manure treatments. This effect was observed both in the fallow and rye cover crop treatments. In experiment 2, NH_3 emissions were generally lower, and only the rye + high manure treatment was significantly greater than the other treatments.

Cumulative N_2O emissions were increased by high manure N treatment (Table 2). In both experiments the highest N_2O emissions were

Table 2 Manure nitrogen added, cumulative N lost as NH_3 and N_2O, NO_3 leaching, soil N, and rye N uptake

Treatment	Manure N added ($g\ N\ m^{-2}$)	NH_3-N volatilized ($g\ N\ m^{-2}$)	N_2O-N emission ($g\ N\ m^{-2}$)	Soil mineral N ($g\ N\ m^{-2}$)	NO_3-N leached ($g\ N\ m^{-2}$)	Cover crop-N ($g\ N\ m^{-2}$)
Experiment 1						
Rye + high manure	19.5 (0.28)	0.0034 (0.0011)	0.232 (0.067)	1.12 (0.348)	0.309 (0.162)	10.2 (0.657)
Rye + low manure	7.53 (0.14)	0.0008 (0.0003)	0.132 (0.017)	0.310 (0.033)	0.024 (0.029)	6.37 (0.391)
Rye, no manure	0	0.0005 (0.0005)	0.106 (0.037)	0.312 (0.165)	0.001 (0.003)	2.95 (0.283)
Fallow + high manure	19.1 (0.30)	0.0066 (0.0011)	0.368 (0.138)	10.5 (0.522)	6.28 (1.14)	
Fallow + low manure	7.51 (0.29)	0.0010 (0.0008)	0.150 (0.035)	3.65 (0.713)	4.821 (0.292)	
Fallow, no manure	0	0.0011 (0.0007)	0.091 (0.010)	1.30 (0.285)	1.51 (0.486)	
LSD 0.05		0.00121	0.0987	0.610	0.789	0.752
Experiment 2						
Rye + high manure	17.9 (0.08)	0.030 (0.017)	0.157 (0.024)	0.597 (0.217)	0.115 (0.053)	10.7 (0.920)
Rye + low manure	2.99 (0.02)	0.011 (0.017)	0.051 (0.016)	0.323 (0.092)	0.002 (0.003)	4.04 (0.535)
Rye, no manure	0	0.003 (0.001)	0.038 (0.008)	0.224 (0.055)	0.008 (0.016)	3.12 (0.450)
Fallow + high manure	17.8 (0.14)	0.002 (0.002)	0.210 (0.023)	16.4 (1.15)	3.77 (0.752)	
Fallow + low manure	2.99 (0.04)	0.001 (0.001)	0.054 (0.012)	4.35 (1.49)	1.74 (0.842)	
Fallow, no manure	0	0.002 (0.001)	0.021 (0.011)	2.53 (0.337)	0.923 (0.138)	
LSD 0.05		0.00147	0.0252	1.17	0.549	1.07

Values in parentheses are standard deviations

measured from the fallow + high manure treatment. The presence of cover crops significantly reduced N_2O emissions at the high manure level in both experiments. At the low manure level, there was a trend of decreased N_2O emissions with the rye cover crop, however, this effect was not significant.

Nitrate leaching losses were significantly lower in the cover crop treatments compared to the fallow treatments. This effect was observed across all three manure levels. In the treatments with cover crops the inorganic N remaining in the soil was significantly lower than the final inorganic N pools in the fallow treatments. In the fallow treatments, the inorganic N remaining in the soil increased significantly with increasing manure-N additions.

Rye cover crop N uptake also significantly increased with increasing manure-N additions. At the high manure-N rates, cover crop N uptake averaged 10.2 and 10.7 g N m^{-2} in experiments 1 and 2, respectively. Average cover crop N uptake at the low manure rates ranged from 4.0 to 6.4 g N m^{-2}, and at the zero manure rate, cover crop N uptake was approximately 3.0 g N m^{-2} in the two experiments.

Because N in the manure was not labeled, we were unable to distinguish between N derived from manure and N derived from the soil in the various N pools we measured. However, we assumed that all treatments had similar levels of soil N mineralization, thus, we estimated the fate of the manure-N equivalent in each pool by subtracting the corresponding no-manure treatment value from the value for the treatments with added manure and expressed the results as percentages of applied manure N (Table 3). Only a small fraction of the manure N was lost as NH_3. In experiment 1, from 0.015% to 0.028% of the equivalent of the applied N was lost from the high manure treatment, and the fallow + high manure treatment was significantly greater than all the other treatments. In experiment 2, the percentages of manure N lost as NH_3 were of the same magnitude as observed in experiment 1, however, there were no significant effects of either cover crop or N application rate. Nitrogen losses in N_2O emissions ranged from 0.35% to 1.45% of applied manure N. Percentages of manure N loss were significantly greater in the no rye + high manure treatment compared to the rye + high manure treatments. The fraction of manure-N remaining in the soil as mineral N ($NO_2 + NO_3 + NH_4$) was significantly lower in the rye treatments compared to the fallow treatments in both experiments. The percentages of manure N lost as NO_3

Table 3 Recovery of manure N equivalents at the end of the experiments

Treatment	NH_3-N volatilized	N_2O-N emissions	Soil mineral N	NO_3-N leached	Cover crop-N	Total
% of manure N added (manure treatment minus no manure/manure N added)						
Experiment 1						
Rye + high manure	0.015 (0.006)	0.64 (0.34)	4.11 (1.78)	1.57 (0.82)	37.3 (3.55)	43.6 (1.08)
Rye + low manure	0.004 (0.004)	0.35 (0.23)	–0.021 (0.43)	0.25 (0.39)	45.4 (5.00)	46.0 (4.63)
Fallow + high manure	0.028 (0.006)	1.45 (0.71)	48.5 (2.15)	25.3 (6.15)		75.3 (6.3)
Fallow + low manure	–0.003 (0.011)	0.80 (0.49)	31.2 (8.75)	44.6 (6.62)		76.6 (4.68)
LSD 0.05	0.011	0.74	7.09	7.0	7.51	7.06
Experiment 2						
Rye + high manure	0.015 (0.010)	0.66 (0.13)	2.09 (1.22)	0.63 (0.29)	42.6 (5.26)	46.0 (5.50)
Rye + low manure	0.027 (0.056)	0.45 (0.53)	3.31 (3.05)	–0.20 (0.12)	30.8 (18.0)	34.4 (16.4)
Fallow + high manure	–0.0002 (0.001)	1.06 (0.13)	78.1 (6.11)	16.0 (4.13)		95.2 (2.11)
Fallow + low manure	–0.0046 (0.003)	1.10 (0.43)	60.3 (49.3)	26.9 (30.8)		88.4 (27.2)
LSD 0.05	0.0438	0.23	38.3	12.1	Ns	22.9

Values in parentheses are standard deviations. ns indicates not significant

in drainage water were not different across manure application rates, but were significantly lower in the presence of cover crops. The percentages of manure N taken up by the rye plants were not affected by manure application rate and ranged from 37.3% to 45.4% in experiment 1 and ranged from 30.8% to 42.6% in experiment 2. By summing all the measured N pools and losses, the total percentage of the equivalent manure N that could be accounted for in the treatments with cover crops ranged from 34% to 46% of the applied manure N. These recoveries were significantly less than those measured for the no-rye treatments where the equivalent of approximately 76% of the manure N was accounted for in experiment 1 and 88.4% to 95.2% was accounted for in experiment 2.

In general, rye shoot, root, and total dry weight increased with increasing manure application (Table 4). In experiment 1, rye shoot dry weight of the high manure > low manure > no manure, and in experiment 2 the high manure > low manure = no manure treatments. Differences in root weight were not as distinct. In experiment 1, the root dry weight of the low manure treatment was greater than the no manure treatment, but not significantly different from the high manure treatment. In experiment 2, there were no differences among the manure levels in root dry weight. For total plant dry weight, the low and high manure levels were significantly greater than the no manure level in experiment 1 and the high manure level was greater than the low and no manure treatments in experiment 2.

In general, shoot and root N concentrations also increased with increasing manure application (Table 4). In both experiments, shoot N concentrations of the high manure treatment > low manure > no manure. Root N concentrations followed the same pattern as the shoots in experiment 2, but in experiment 1 the high manure treatment had a greater root N concentration than both the low and no manure treatments.

Drainage collected in experiments 1 and 2 was significantly less for the rye treatments than the fallow treatments (Table 5). Treatments with a rye cover crop had less than 65% of the drainage of the fallow treatments in experiment 1. In experiment 2, the rye treatments had less than 69% of the drainage of the no-rye treatments. Manure treatments also significantly affected cumulative drainage. In experiment 1, the high manure and no manure treatments had more drainage than the low manure treatments. In experiment 2, the no manure treatment had more drainage than both the high and low manure treatments. The interaction of cover crop and manure treatments was significant for both experiments. In experiment 1, there was no difference in drainage among the fallow treatments at any of the three manure levels, whereas the rye treatment at the low manure level had significantly less drainage than the rye treatments at the high and

Table 4 Rye cover crop growth and N content

	Shoot dry weight g m^{-2}	Root dry weight	Total plant dry weight	Shoot N g g^{-1}	Root N
Experiment 1					
Rye + high manure	395.5 (33.5)	256.1 (35.2)	651.6 (65.1)	0.019 (0.0006)	0.010 (0.0010)
Rye + low manure	280.9 (23.5)	315.6 (83.5)	596.5 (101.2)	0.014 (0.0015)	0.008 (0.0008)
Rye, no manure	152.7 (35.7)	202.7 (38.0)	355.5 (44.6)	0.009 (0.0002)	0.008 (0.0004)
LSD 0.05	32.2	96.5	107.5	0.002	0.001
Experiment 2					
Rye + high manure	418.2 (42.4)	230.6 (25.8)	648.8 (64.0)	0.020 (0.0021)	0.010 (0.0005)
Rye + low manure	218.0 (42.8)	224.9 (31.5)	442.9 (60.3)	0.011 (0.0005)	0.008 (0.0005)
Rye, no manure	210.7 (27.8)	201.7 (39.1)	412.5 (60.9)	0.008 (0.0005)	0.007 (0.0005)
LSD 0.05	66.1	67.5	123.3	0.002	0.001

Values in parentheses are standard deviations

Table 5 Water drainage, evapotranspiration, and soil water content in cover crop and manure treatments

	Drainage (mm)	Cumulative evapotranspiration (mm)	Average gravimetric water content (gg^{-1})
Experiment 1			
Rye + high manure	61.1 (6.9)	139.6 (7.6)	0.094 (0.005)
Rye + low manure	43.7 (5.9)	149.4 (7.0)	0.092 (0.004)
Rye, no manure	62.9 (12.4)	116.6 (12.1)	0.112 (0.010)
Fallow + high manure	107.6 (7.7)	79.6 (7.3)	0.140 (0.003)
Fallow + low manure	100.5 (6.1)	84.2 (6.5)	0.140 (0.006)
Fallow, no manure	97.6 (4.90)	84.9 (5.3)	0.132 (0.004)
LSD 0.05	11.4	11.1	0.009
Experiment 2			
Rye + high manure	26.9 (8.5)	118.5 (9.6)	0.111 (0.005)
Rye + low manure	32.7 (3.0)	97.3 (4.8)	0.115 (0.003)
Rye, no manure	43.5 (9.4)	80.2 (10.2)	0.115 (0.004)
Fallow + high manure	67.4 (2.1)	69.7 (1.7)	0.138 (0.003)
Fallow + low manure	63.2 (2.8)	73.2 (2.8)	0.137 (0.010)
Fallow, no manure	63.9 (4.7)	70.2 (4.0)	0.130 (0.009)
LSD 0.05	7.8	4.6	0.004

Values in parentheses are standard deviations

no manure level. Similarly, in experiment 2 there was no difference in drainage among the fallow treatments at any manure level, but the rye treatment without manure had more drainage than rye with added manure. This indicates that the effect of manure level on cumulative drainage was the result of increased rye growth with manure application.

Cumulative evapotranspiration in experiments 1 and 2 was significantly greater for the treatments with cover crops than those without cover crops (Table 5). Treatments with a rye cover crop had more than 137% of the evapotranspiration of the no-rye treatments in experiment 1. In experiment 2, the rye treatments had more than 109% of the evapotranspiration of the fallow treatments. In both experiments, there was no difference in evaportranspiration among the fallow treatments at the three levels of manure, thus the differences in evapotranspiration among manure levels for the cover crop treatments may reflect the increased rye growth in response to manure application.

The soil water contents in experiments 1 and 2 were significantly drier for treatments with cover crops than those without cover crops (Table 5). Treatments with a rye cover crop had less than 88% of the soil water of the no-rye treatments in experiments 1 and 2. The main effects of the manure treatments did not affect soil water content in experiment 1, but in experiment 2 soil in the low manure level was wetter than the no manure level. The interaction of cover crop and manure treatments was significant for both experiments. For the treatments without cover crops, there was no significant difference in water content among the manure levels in experiment 1, but in experiment 2, soil in the no manure level was drier than low and high manure levels. For the rye treatments, soil in the low manure level was significantly drier than the no manure level in experiment 1 and in experiment 2 soil in the high manure level was drier than the low and no manure levels.

Discussion

Managing manure in agricultural cropping systems to retain nutrients in the soil and prevent losses presents difficult challenges, especially for N. Ammonia volatilization from manure applied to soil has been reported to be a significant mechanism of N loss. Thompson and Meisinger (2004) observed large NH_3 volatilization rates and summarized that 30–70% of the NH_4-N from surface applied cattle manure slurry in the mid-Atlantic region of the US could be lost as NH_3. These values are in the range of estimates derived from a model of NH_3 volatilization losses using a large European database, where cumulative NH_3-N losses ranged from 32% to 45% of applied NH_4-N for cattle slurry and 25–31% of applied NH_4-N for swine slurry (Sogaard et al. 2002). The NH_3-N losses we measured were much lower, and we observed NH_3-N volatilization losses of <0.05% of the applied NH_4-N. One likely factor contributing to our low NH_3 fluxes was our manure application method. We applied the manure slurry to a trench cut into the soil and immediately covered the trench with soil. Soil incorporation of manure has been shown to substantially reduce ammonia losses (Thompson and Meisinger 2002; Sommer and Hutchings 2001). Another factor that may have contributed to our low NH_3 emissions relative to previously published field emissions is the low chamber exchange volumes used in our measurement protocols. Kissel et al. (1977) recommended air exchange rates in field-deployed chambers of >15 exchanges/minute to mimic field wind speeds. The NH_3 measurement protocol of our study resulted in <2 headspace changes/hour, and could have resulted in lower NH_3 emissions than would have been observed in the field. However, the chamber exchange rates we used were likely more reflective of the growth chamber conditions in our study. Despite the fact that these conditions did not duplicate field conditions, the ammonia emissions we measured would be valid as comparisons across treatments, and we did observe significant treatment differences.

Leaching of manure N, in the form of NO_3 is potentially another significant loss mechanism. Bakhsh et al. (2005) reported significantly higher NO_3 leaching from plots receiving liquid swine manure compared to UAN fertilized plots. They attributed the difference to a build up of organic N pools, which resulted in greater subsequent N mineralization and increases in the soil NO_3 pool. Better management of the soil NO_3 pool is a general recommendation for reducing NO_3 leaching losses (Sharpley et al. 1998). The use of cover crops is known to be an effective strategy in reducing the soil nitrate pool. Meisinger et al. (1991), in a review of past studies on cover crops, summarized that NO_3 concentrations in leachate can be reduced from 20% to 80% by using cover crops.

Results of our controlled environment experiments demonstrated that a rye cover crop significantly reduced NO_3 leaching. We observed that the equivalent of less than 2% of applied manure N was lost by leaching in the presence of cover crops, whereas without cover crops NO_3 leaching losses ranged from 10% to 45% of the equivalent of the applied manure-N. The rye cover crop most likely reduced leaching losses of NO_3 by a combination of the accumulation of N in plant biomass, a reduction in soil NO_3 concentration, and a reduction of drainage volume.

With regard to a nitrogen balance, the N taken up by the cover crop and the gaseous and leaching losses could not completely account for the added manure N in the rye + manure treatments. In the presence of cover crops, we were only able to recover the equivalent of 34–46% of the added manure N, whereas, in the absence of cover crops we could account for approximately 76% of the added manure N in experiment 1 and 88–95% of the added manure N in experiment 2. Most of the equivalent manure N accounted for in the cover crop treatments was in the cover crop biomass, with little residual N in the soil inorganic N pools and low leaching and gaseous losses.

There are several possibilities that may explain the apparent ''missing'' manure N in our partial N balance for the cover crop treatments. Total gaseous N losses by denitrification were not measured, thus it is possible that differences in denitrification between the cover crop and no-cover crop treatments could be responsible for the differences in N applied and N recovery observed. However, we do not think this is likely, for several reasons. First, throughout incubations of both experiments, soil water content in the cover crop treatments was less than or equal to that of the fallow treatments. Table 5 shows that the average soil water contents measured just before watering each week were lower in treatments with cover crops. Immediately after watering and initial drainage, all treatments had approximately the same water content because all buckets received an equal amount of water each week. Second, living plants have been shown to effectively compete with soil microorganisms for available nitrate, thus reducing gaseous nitrogen loss by denitrification (Haider et al. 1985; Smith and Tiedje 1979). Smith and Tiedje (1979) observed that in the presence of living corn roots, denitrification potential was greater; however, due to root uptake of available NO_3, expression of this potential was limited. These investigators concluded that the competition for available NO_3 between denitrifying bacteria and plant roots reduced denitrification when NO_3 concentrations were low. Similar results were observed by Haider et al (1985) who found that under NO_3 limiting conditions, denitrification was not stimulated by corn or wheat *(Triticum aestivum* L.) roots compared to unplanted soil, but when sufficient NO_3 was present, denitrification was found to increase in the presence of plant roots (Haider et al. 1987). In our study, although we did not measure soil NO_3 concentrations throughout the incubation period, the low NO_3 leaching losses we observed in the rye treatments and the low inorganic N levels at the end of the experiments indicate that soil NO_3 pools were likely low in treatments with rye cover crops. Finally, we suspect that there were not large differences in denitrification between the fallow and rye treatments because N_2O emissions were of similar magnitude and there are no obvious reasons for large differences in the N_2O:N_2 ratio of the denitrification process between treatments.

Another possible explanation for our observed lower recoveries of manure-N in the rye treatments compared to the fallow treatments could be differences in N mineralization/immobilization processes. There are conflicting reports in the literature concerning the influence of plants on net N mineralization. Some studies have reported a positive effect of living plants on net N mineralization. Possible mechanisms underlying this stimulation include increased microbial activity due to root exudation increased microbial activity due to wetting and drying cycles induced by the plant, as well as decreased immobilization due to competition for N by the plant (Dormaar 1990). Griffiths and Robinson (1992) proposed a model whereby carbon released by plant roots stimulated microbial activity, resulting in stimulated soil organic matter degradation and N immobilization. This N was then released when bacteria were consumed by nematodes, resulting in plant stimulated net N mineralization. This concept was an extension of previous work by Clarholm (1985) and Ingham et al. (1985). Clarholm (1985) demonstrated that root C inputs or exogenous C additions (glucose) resulted in a stimulation of soil organic matter mineralization and N immobilization by bacteria. Subsequent grazing of bacteria by protozoa resulted in increased net N mineralization. In our experiments, a positive effect of living plants on net mineralization would most likely have the greatest influence on N uptake by rye plants in the no-manure treatment. In both experiments, however, the total amount of nitrogen measured for the rye-no manure treatment was not different from that measured for the fallow-no manure treatment, indicating that rye plants did not substantially increase net N mineralization in the no manure treatments.

In contrast, others have reported no stimulation of net N mineralization by growing plants, or a decrease in net N mineralization. Bremer and

Kuikman (1997) observed that plant effects on net N mineralization were sensitive to the inorganic N status of the soil. These investigators observed that in the presence of high NH_4 levels combined with added straw residue, net N mineralization was lower in soil planted to wheat than in fallow pots. This decrease in net N mineralization was reported to be due to increased microbial immobilization. In our experiment, at the high manure level, our results may indicate a decrease in net mineralization, similar to observations of Bremer and Kuikman (1997). However, it may be that in our experiment the higher inorganic N levels in the fallow + high manure treatments enhanced mineralization, whereas in the presence of rye, the inorganic N concentrations were kept low, even in treatments with added manure. We were unable to directly measure cover crop or manure effects on mineralization and immobilization of the organic N pool, given the large size of this pool relative to the quantities of manure N added. Soil organic N levels at the termination of experiments 1 and 2 were 275.2 g N m^{-2} (±12.5) and 280.4 g N m^{-2} (±11.2), respectively (values in parentheses are 95% confidence intervals). There were no significant effects of either cover crop or manure treatments. However, increased N immobilization in the presence of cover crops + manure or enhanced mineralization with no cover crops + manure of the magnitude necessary to account for our observed discrepancies in N balance (4.0–10.9 g N m^{-2}) is within the error ranges we measured for the soil organic N pool. We suspect manure additions stimulated mineralization of soil organic N in the fallow treatments. It is possible that both processes were occurring. Our recoveries of equivalent manure N for the fallow treatments are unusually high, especially in experiment 2, which would seem to indicate that fallow high and low manure treatments have more N mineralized from the soil organic N than the fallow no manure treatment.

Despite the fact that we were unable to perform a complete N balance, we can draw several conclusions from our study. The most striking observations are the effects of a rye cover crop on water and manure-N partitioning. The rye cover crop accumulated a significant proportion of manure-N, greatly reduced the amount of NO_3 lost in drainage water, reduced soil inorganic N levels, increased evapotranspiration, and reduced cumulative drainage. Also, there was a significant reduction in N_2O emissions in the presence of the rye cover crop, but no consistent effect of a cover crop on NH_3 volatilization. Despite the clear benefit of cover crops, additional work must resolve the apparent interactions of manure and of cover crops on N mineralization/immobilization processes.

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